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GROUND MOTION TIME HISTORIES FOR USE IN PERFORMANCE BASED SEISMIC ENGINEERING

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P. Somerville and N. Collins

URS Group, Inc.

566 El Dorado Street
Pasadena, CA 91101

Tel: (626) 449-7650
Fax: (626) 449-3536

Email: paul_somerville@urscorp.com

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Principal Investigators: Paul Somerville, Nancy Collins

URS Group, Inc.
566 El Dorado Street
Pasadena, CA 91101
Tel: (626) 449-7650
Fax: (626) 449-3536
Email: paul_somerville@urscorp.com

ABSTRACT

The objective of this project is to develop regionally specific ground motion time histories for the Central and Eastern United States and make them available for use in performance based seismic engineering. In the central and eastern United States, recorded ground motions are sparse, giving rise to a need to use time histories generated using simulation procedures. Currently, time histories generated using a simplified stochastic simulation procedure (Frankel et al., 1996) are available on the USGS website (under "Interactive Deaggregation"). By providing recorded time histories where available, and time histories simulated using more rigorous methods (based on shear dislocation fault models and Greens' functions) where suitable recorded time histories are not available, this project aims to develop more realistic time histories to complement the stochastic time histories available from the USGS website.

Suites of time histories were developed for 25 major cities in the central and eastern United States. The suites of time histories are for three probability levels (2% in 50 years, 10% in 50 years, and 50% in 75 years, i.e. return periods of 2,475, 475, and 108 years), which are used in the performance based design guidelines of FEMA 273 (1997). The time histories were scaled to response spectra for soft rock site conditions, derived from the USGS National Seismic Hazard Maps, for these return periods. The time histories were derived from two sources: strong motion recordings, and a broadband Green's function ground motion simulation procedure that has been validated against recorded data. For each return period for each of 25 cities, a suite of ten magnitude - distance combinations was prepared to represent the seismic hazard, based on the deaggregation of the seismic hazard provided by the USGS.

GROUND MOTION NEEDS OF PERFORMANCE BASED SEISMIC ENGINEERING

Seismic building codes in the United States have traditionally had the goal of protecting life safety by preventing the collapse of structures in the event of a specific threshold earthquake. Since that level is associated with mean annual frequencies that are too large relative to conventionally tolerable life safety levels, the engineer must depend on the capacity, not rigorously based, of a structure to resist forces exceeding this level. The analysis of the building is done using a linear elastic model with ground motions, specified in the form of a response spectrum, that have been reduced by a code-tabulated factor (the R factor) that accounts for this capacity. This linear elastic analysis provides a check on forces and deformations in the structure in its undamaged state, but does not directly address the behavior of a building that is yielding and thus deforming in a non-linear manner.

Current trends in the development of building codes have all embraced the concept of performance based design, and conceptual frameworks of that approach have been developed in SEAOC Vision 2000 (SEAOC, 1996) and FEMA-273 (FEMA, 1997). In contrast to the traditional approach, performance-based design requires an explicit prediction of the structure's performance at each of several ground motion levels corresponding to a set of performance objectives. The performance objectives may range from continued function of the building during relatively small, frequent ground motions; to limiting damage below the life safety threshold in severe, less frequent ground motions; to prevention of collapse for very severe, infrequent ground motions. Each performance objective is associated with an annual probability of occurrence, with increasingly undesirable performance characteristics caused by increasing levels of strong ground motion having decreasing annual probability of occurrence (Figure 1).

The relationship between the ground motion level and its annual probability of occurrence is described by a hazard curve, as shown for Boston in Figure 2. This example is from the National Seismic Hazard Maps produced by the USGS in 1996, which form the basis for the NEHRP Provisions that are used in building codes in the United States. The hazard curve is generated in a probabilistic seismic hazard analysis that takes into account the ground motions from the full range of earthquake magnitudes that can occur on each fault or source zone that can affect the site. It is calculated from the rate of occurrence of these earthquakes, their distance from the site, and the attenuation of ground motion between the earthquakes and the site. The horizontal axis of Figure 2 shows the peak acceleration, the vertical axis on the left shows the annual frequency of exceedance of the peak acceleration, and the axis on the right shows its inverse, the corresponding average return period. The hazard curve in Figure 2 is for peak acceleration (response spectral acceleration at zero period) on soil, but the PSHA can produce analogous hazard curves for response spectral acceleration for a suite of periods. From these hazard curves, a suite of response spectra corresponding to several return periods can be constructed, as shown for Boston at the top of Figure 3. The products of a PSHA are ideally suited for performance based design because they specify the largest ground motions that are expected to occur for a range of different annual probabilities (or return periods).

For performance based design to be truly effective, the ground motions need to be specified not only as response spectra, but also by suites of strong motion accelerograms - time histories in engineering parlance- for input into time-domain non-linear analyses of structures. This is because response spectrum analysis, upon which nearly all current structural design is based, uses modal superposition and therefore does not address the non-linear response that is the essence of building damage and failure. Time histories whose response spectra are scaled to the target response spectra (derived from the USGS maps) at the top of Figure 3 are shown at the bottom of Figure 3. The match between the target spectra and the spectra of the time histories is shown in the middle of Figure 3. In order to develop and test methods for performance based design, engineers such as those at professional engineering design offices and at the three National Earthquake Engineering Centers need time histories for input into computer-based dynamic analysis of structures. Time histories are also needed as inputs into experimental earthquake engineering facilities by researchers at these Centers and at other laboratories associated with the Network for Earthquake Engineering Simulation. Papers by Carballo and Cornell (2002), Luco and Cornell (2003), Shome et al (1998) and Wen and Wu (2001) describing these applications are listed in the Bibliography.

DEVELOPMENT OF RESPONSE SPECTRA

A set of 25 cities with population of 1 million or more, shown in Figure 4 and listed in Table 1, was selected for the development of time histories. For each city, response spectra were derived from the USGS National Seismic Hazard Maps (Frankel et al., 1996; 2000). The mapped ground motions are for soft rock conditions (the boundary between NEHRP site categories S_B and S_C). The response spectra are for three probability levels (2% in 50 years, 10% in 50 years, and 50% in 75 years, i.e. return periods of 2,475, 475, and 108 years), which are used in the performance based design guidelines of FEMA 273 (1997).

Table 1. List of Cities for which Time Histories were Developed

Location	Latitude	Longitude
Boston MA	42.358ºN	71.060ºW
New York NY	40.714ºN	74.006ºW
Philadelphia PA	39.952ºN	75.164ºW
Washington DC	38.895ºN	77.037ºW
Buffalo NY	42.886ºN	78.879ºW
Pittsburgh PA	40.441ºN	79.996ºW
Cleveland OH	41.499ºN	81.696ºW
Detroit MI	42.331ºN	83.046ºW
Cincinnati OH	39.162ºN	84.457ºW
Indianapolis IN	39.768ºN	86.158ºW
Chicago IL	41.850ºN	87.650ºW
Milwaukee WI	43.039ºN	87.906ºW
Minneapolis MN	44.980ºN	93.264ºW
Atlanta GA	33.749ºN	84.388ºW
New Orleans LA	29.954ºN	90.075ºW
St. Louis MO	38.627ºN	90.198ºW
Kansas City MO	39.100ºN	94.578ºW
Dallas TX	32.783ºN	96.800ºW
Houston TX	29.763ºN	95.363ºW
Miami FL	25.774ºN	80.194ºW
Tampa FL	27.947ºN	82.459ºW
Denver CO	39.739ºN	104.984ºW
Charleston SC	32.776ºN	79.931ºW
Augusta GA	33.471ºN	81.975ºW
Savannah GA	32.083ºN	81.100ºW

Maximum Considered ground motion maps for use in design were derived from the USGS probabilistic ground motion maps in the 1997 NEHRP Provisions (FEMA, 1998) by the Building

Seismic Safety Council. In most regions, these ground motions are identical to those for 2% in 50 years, so the time histories for 2% in 50 years can be used to represent the Maximum Considered ground motions.

SELECTION OF MAGNITUDE-DISTANCE COMBINATIONS FOR TIME HISTORIES

The probabilistic response spectra mapped by the USGS represent the aggregated contributions of a range of earthquake magnitudes occurring at various rates on each of several discrete faults or seismic source zones located at various distances from the site, and include the effect of random variability in the ground motions for a given magnitude and distance. However, in order to provide ground motion time histories that represent the response spectrum, we must choose one or more discrete combinations of magnitude, distance and epsilon, to represent the probabilistic ground motion. The parameter epsilon is defined as the number of standard deviations above or below the median ground motion level for that magnitude and distance that is required to match the probabilistic spectrum. The magnitude, distance, and epsilon values are estimated through deaggregation of the probabilistic seismic hazard (Bazzurro and Cornell, 1999; Chapman, 1995; Cramer and Peterson, 1996; Harmsen, 2001, Harmsen et al., 1999; McGuire, 1995). These magnitude, distance and epsilon values have been mapped by Harmsen et al. (1999) for the central and eastern United States and by Harmsen and Frankel (2001) for the western United States.

The deaggregations for 1 second period spectral acceleration for 2% in 50 years are shown for Atlanta in the form of magnitude, distance and epsilon combinations in Figure 5. The contributions to the ground motions come from a wide range of seismic sources, which generally consist of increasingly large earthquake magnitudes at increasingly large distances from Atlanta. The three main sources contributing to the seismic hazard at Atlanta include the gridded seismicity within about 150 km of Atlanta, the Charleston seismic zone located about 350 km from Atlanta, and the New Madrid seismic zone located about 550 km from Atlanta. Figure 6 explicitly locates on a map the combinations of magnitude and distance that contribute to the hazard at a single site, Atlanta. This kind of map facilitates the selection of a suite of magnitudes and distances that are most representative of the hazard. Examples of scaled response spectra and time histories that represent the seismic hazard at Atlanta for different return periods are shown in Figures 7 through 12.

The deaggregation differs for different response spectral periods. In some cases, there are very large differences, with the shorter periods controlled by smaller, closer earthquakes and the longer periods controlled by larger, more distant earthquakes. Consequently, it is not generally possible to develop ground motion time histories that simultaneously represent the deaggregated hazard at all periods. If the natural period of a structure is specified, then a set of time histories can be provided using the deaggregation of the hazard at that period. The Interactive Hazard part of the USGS website does this – it provides ground motion time histories simulated using the stochastic method for a specified natural period and return period. In this report, we have provided time histories that are based on the deaggregation at periods of 0.3 and 1.0 seconds. We selected some time histories to represent the deaggregation at 0.3 seconds and others to represent the deaggregation at 1.0 seconds. Time histories that were representative of the average of the deaggregations were also selected in some instances.

SELECTION OF RECORDED GROUND MOTION TIME HISTORIES

The data set of recorded ground motions in the central and eastern United States is very sparse. A set of candidate three-component recordings from four earthquakes was selected, as listed in Table 2. Recordings having late triggers were excluded from this set.

Table 2. Recordings of eastern North American earthquakes

Location	**Date**	**Magnitude** (M_w)	**Station**	**Distance** (km)
New Hampshire	1/19/82	4.5	Franklin Falls dam	6
			Union Village dam	59
Miramichi, New Brunswick aftershock	3/31/82	4.6	Indian Brook	2
			Mitchell Lake Road	7
Darmstadt, Indiana	6/18/02	4.6	Columbus, Kentucky	175
			Hickman, Kentucky	200
			Ridgely, Tennessee	245
Saguenay, Quebec	11/25/88	5.8	SM16	43
			SM17	64
			SM20	90
			SM8	93
			SM5	109
			SM1	113
			SM10	114
			SM9	122
			SM2	149

PROCEDURES USED TO SIMULATE GROUND MOTION TIME HISTORIES

We used recorded ground motion time histories where suitable ones were available. However, in most regions of the central and eastern United States, sufficient recorded time histories are not available, and in these cases we used broadband strong motion simulations for the magnitude and distance combinations indicated by the deaggregations. These simulated time histories can be generated to represent the magnitudes and distances that constitute the seismic hazard at a particular location.

The broadband Green's function method that we used for generating ground motion time histories has a rigorous basis in theoretical and computational seismology, and uses the elastodynamic representation theorem and Green's functions. This procedure was used by us in a previous USGS project to generate large suites of ground motion simulations, which were then used to develop a ground motion model for the central and eastern United States (Somerville et al., 2001). The USGS used this ground motion model, along with other ground motion models, to generate the 2000 version of the USGS National Seismic Hazard Maps.

In the broadband ground motion simulation procedure of Somerville et al. (2001), the earthquake source is represented as a shear dislocation on an extended fault plane, whose radiation pattern, and its tendency to become subdued at periods shorter than about 1 sec, are accurately represented. Wave propagation is represented rigorously by Green's functions computed for the seismic velocity structure that contains the fault and the site, or by empirical Green's functions derived from strong motion recordings of small earthquakes. These Green's functions contain both body waves and surface waves. The ground motion time history is calculated in the time domain using the elastodynamic representation theorem. This involves integration over the fault surface of the convolution of the slip time function on the fault with the Green's function for the appropriate depth and distance.

To simulate broadband time histories, the ground motions are computed separately in the short period and long period ranges, and then combined into a single broadband time history (e.g. Somerville et al., 1996). The use of different methods in these two period ranges is necessitated by the observation that deterministic behavior (ability to model peak amplitudes and waveforms) predominates at long periods (longer than about 1 second) and stochastic behavior (ability to predict amplitudes but not waveforms) predominates at short periods. The broadband Green's function procedure that we used contains fewer simplifications than does the stochastic model used by Atkinson and Boore (1995), Frankel et al. (1996) and Toro et al. (1997). The Green's functions that are used in this procedure can be calculated from known crustal structure models, facilitating the use of the procedure in regions where recorded data are sparse or absent.

The earthquake source models used to generate time histories were based on the source scaling relations for eastern North American earthquakes derived by Somerville et al. (2001). These relations, listed in Table 3, allow us to construct earthquake source models without resorting to a priori assumptions about the shape of the source spectrum, as is done in the stochastic approach. The source parameters used to simulate ground motion time histories are listed in Table 4.

Table 3. Scaling Relations of Slip Models of Crustal Earthquakes in Eastern North America

Rupture Area vs. Seismic Moment:	$A = 8.9 \times 10^{-16} \times M_o^{2/3}$
Average Slip vs. Seismic Moment:	$D = 3.9 \times 10^{-7} \times M_o^{1/3}$
Combined Area of Asperities vs. Seismic Moment*	$A_a = 2.0 \times 10^{-16} \times M_o^{2/3}$
Area of Largest Asperity vs. Seismic Moment*	$A_l\ (km^2) = 1.4 \times 10^{-16} \times M_o^{2/3}$
Radius of Largest Asperity vs. Seismic Moment*	$r_l\ (km) = 6.7 \times 10^{-9} \times M_o^{1/3}$
Average Number of Asperities*	2.6
Area of Fault Covered by Asperities*	0.22
Average Asperity Slip Contrast*	2.0
Hypocentral Distance to Center of Closest Asperity Vs. Moment*	$R_A = 1.35 \times 10^{-8} \times Mo^{1/3}$
Slip Duration vs. Seismic Moment	$T_R = 3.75 \times 10^{-9} \times Mo^{1/3}$
Spatial Wavenumber Along Strike (1/km)*	log kx = 1.92 - 0.5 M
Spatial Wavenumber Down Dip (1/km)*	log ky = 2.13 - 0.5 M

* assumed to be the same as for shallow crustal earthquakes in tectonic regions

The crustal model used in the simulations is described by Somerville et al. (2001) and listed in Table 5. This is the Mid-continent structure that we developed in the course of the EPRI (1993) project. In that project, we regionalized the crustal structure of the central and eastern United States into 16 regions. The ground motion attenuation characteristics of one of these 16 regions, the Mid-continent region, were found to be most closely representative of the attenuation characteristics of these 16 regions. The surface shear wave velocity of this model corresponds to NEHRP Site Category S_A (hard rock). We did not attempt to adjust these time histories to be representative of NEHRP Site Category $S_{B/C}$ (soft rock) that is used to represent the ground motions in the USGS National Seismic Hazard Maps. We consider that the simulated time histories are a reasonably good representation of NEHRP Site Category $S_{B/C}$ overall, but may tend to underestimate the ground motions at periods longer than 1 second.

Table 4. Parameters for Ground Motion Simulations

PARAMETER	RANGE OF VALUES
Magnitude	Mw 6.0 - 7.5
Other Source Parameters	Scaling with magnitude is described in Table 3
Distance	0 - 500 km
Crustal Structure	Midcontinent model: α, β, ρ, Q (h) (see Table 5); K = 0.006
Site Condition	Hard Rock (Vs = 2.83 km/sec)
Centroid Depth	Approx. 5.0, 10, and 20.0 km
Mechanism	Reverse
Site Locations	Equally spaced radially about the top center of the fault

Table 5. Mid-Continent Crustal Structure Model

Depth to Top (km)	Thickness (km)	P wave vel. (km/sec)	S wave vel. (km/sec)	Density (gm/cc)	P wave Q	S wave Q
0	1	4.9	2.83	2.52	1000.0	500.0
1	11	6.1	3.52	2.71	1500.0	750.0
12	28	6.5	3.75	2.78	2000.0	1000.0
40	-	8.0	4.62	3/35	2500.0	1250.0

SELECTION OF TIME HISTORIES

For several reasons, representation of the seismic hazard at a site by means of ground motion time histories generally requires the use of suites of time histories. First, the hazard consists of contributions from multiple magnitude - distance combinations, while each time history can only represent a single combination. Second, the nonlinear response of a structure to ground motion depends on the phasing of the ground motion, such that different responses are obtained from time histories that have the same or similar response spectra. We selected a suite of ten magnitude - distance combinations to represent the various contributors to the seismic hazard for each of three return periods for each city, using the deaggregation of the seismic hazard provided by the USGS website.

The deaggregation differs for different response spectral periods. In some cases, there are very large differences, with the shorter periods controlled by smaller, closer earthquakes and the longer periods controlled by larger, more distant earthquakes. Consequently, it is not generally possible to develop ground motion time histories that simultaneously represent the deaggregated hazard at all periods. If the natural period of a structure is specified, then a set of time histories can be provided using the deaggregation of the hazard at that period. The Interactive Hazard part of the USGS website does this – it provides ground motion time histories simulated using the stochastic method for a specified natural period and return period. In this report, we have provided time histories that are based on the deaggregation at periods of 0.3 and 1.0 seconds. Where there are large differences between the two deaggregations, we used separate time histories representing the different deaggregations. Where the differences were smaller, we used time histories that were representative of the average of the deaggregations.

Each suite of ground motions contains time histories that are representative of the median and modal values of distance and magnitude, as well as other combinations of magnitude and distance that contribute significantly to the hazard.

Three time histories were chosen to represent the mean values of magnitude and distance. These values represent the average magnitude and distance values over a variety of seismic sources, and in some cases do not represent an actual seismic source. Accordingly, these three time histories were supplemented by four more that represent the magnitude – distance combinations of actual seismic sources that contribute significantly to the seismic hazard.

An additional three time histories were chosen to represent the modal values of magnitude and distance. In some cases, the modal values are from the gridded seismicity. In other cases, the modal values are from specific earthquake sources, such as the Charleston seismic zone and the New Madrid seismic zone. In the latter cases, the four time histories described above that represent the median ground motions are derived from the gridded seismicity, not the overall seismicity.

In addition to the magnitude and distance criteria derived from the deaggregation, we also used the epsilon value (specifically, the epsilon – zero value) from the deaggregation in selecting the time histories (Hamsen, 2001). Using our simulation procedure, we generated large suites of ground motions for a given magnitude and distance. The variability among these simulations represents the same kind of variability that is described by the epsilon in the deaggregation. This allows us to choose time histories that have not only the appropriate magnitude and distance, but also the appropriate ground motion level with respect to the median ground motion level for that magnitude and distance. The epsilon value of each simulation was measured with respect to the median response spectral level given by the ground motion model of Somerville et al. (2001). Time histories for the required magnitude, distance and epsilon were selected whose response spectra had the best fit, measured using an L1 norm, to the median response spectrum, adjusted by the epsilon value, from the Somerville et al. (2001) model.

SCALING OF TIME HISTORIES

The ground motion time histories were scaled to match the average horizontal component of the response spectrum of the time histories to the USGS probabilistic spectrum. The scaling was done using a weighted average over a range of periods, using an L1 norm. The weights given to the periods were 1/4 each for periods of 0.3, 0.5 and 1 second, and 1/8 each for periods of 0.2 and 2.0 seconds. This weighting scheme is centered on a period of 0.5 seconds. The time histories can be rescaled using any desired alternative weighting scheme. For example, if the natural period of a structure is at 1.0 second, then the time histories can be scaled so that their response spectra match the USGS probabilistic spectrum at a period of 1.0 second.

This scaling procedure does not involve any modification of the shape of the response spectrum. If a suite of time histories is to be used in the analysis of a structure, it is considered preferable to use such time histories, rather than ones that have been modified so that their response spectral shape matches the probabilistic hazard response spectrum. This is because the spectral matching procedure produces time histories that are artificially broadband and do not have peaks or troughs in their response spectra. Such peaks and troughs are characteristic of actual ground motions, and affect the nonlinear response of structures.

DESCRIPTION OF TIME HISTORY PRODUCTS

Suites of time histories were generated for each of 25 cities. For each city, a suite of ten time histories for each of three return periods was developed, for a total of 750 three-component time history sets. These time histories are provided in a CD ROM that contains both the scaled versions and the unscaled versions of the time histories. The CD ROM also contains tables describing the time histories, and plots of the time histories and response spectra. These tables and time history and response spectra plots are numerous to display in a report, but we have illustrated them in this report using the city of Atlanta as an example.

Table 6 lists the target magnitude-distance pairs, together with their epsilon values, that represent the deaggregation of the probabilistic response spectra at Atlanta for each of the three return periods, and the magnitude and distance combinations, as well as additional parameters, of the corresponding time histories that were used to represent these magnitude-distance pairs. A detailed legend explaining the contents of Table 6 is provided in Table 7.

Figures 7, 8 and 9 compare the response spectra of the three components of each time history for Atlanta with the probabilistic response spectrum derived from the USGS National Seismic Hazard Maps. The upper and lower labels in these figures contain the deaggregation parameters and the selected time history parameters respectively, which are listed in Table 6 and explained in Table 7. Figures 10, 11 and 12 show three component acceleration, velocity and displacement time histories of one of the time histories for Atlanta for each return period; with labels at top explained in Tables 6 and 7.

As described above, the response spectrum of an individual earthquake is not necessarily expected to be similar to a probabilistic hazard response spectrum, because the latter contains contributions from a broad range of earthquake magnitudes and distances. Nevertheless, in general, the shape of the response spectra of the ground motion time histories is reasonably similar to that of the USGS probabilistic hazard spectra at periods of one second and less. However, at periods longer than one second, the response spectra of the time histories generally decrease with increasing period more rapidly than do the probabilistic spectra. This may be due in part to differences between the ground motion models that were used to generate the probabilistic seismic hazard, especially the Frankel model (Frankel et al., 1996) and the ground motion model that was used to generate the time histories in this project (Somerville et al., 2001). Also, the time histories were simulated using a surface shear wave velocity corresponding to NEHRP Site Category S_A (hard rock). We did not attempt to adjust these time histories to be representative of NEHRP Site Category $S_{B/C}$ (soft rock) that is used to represent the ground motions in the USGS National Seismic Hazard Maps. We consider that the simulated time histories are a reasonably good representation of NEHRP Site Category $S_{B/C}$ overall, but may tend to underestimate the ground motions at periods longer than 1 second.

Table 6. Deaggregation Parameters and Time History Parameters for Atlanta *

RP	DEAGGREGATION					TIME HISTORY						
years	**Type**	**Md**	**Rd**	**ε_0**	**T**	**M**	**R**	**Depth**	**Slip**	**Hypo**	**Az**	**Scale**
2475	Mean	6.54	172.4	0.98	0.3	6.5	200	8-11	07	0	330w	7.510
	Mean	6.82	232.4	1.08	avg	7.0	200	1-5	08	0	130e	4.746
	Mean	7.10	292.4	1.18	1.0	7.0	200	7-11	06	-	290w	3.857
	Modal	7.23	135.3	0.02	0.3	7.0	120	1-5	03	-	150e	2.937
	Modal	7.23	135.3	0.02	0.3	7.0	120	7-11	09	+	030e	2.369
	Modal	8.00	513.1	1.10	1.0	7.5	400	2-9	08	0	050e	6.109
	Frankel	6.42	137.5	0.83	0.3	6.5	120	3-6	07	0	150e	5.691
	Toro	6.62	155.4	1.02	1.0	6.5	120	8-11	05	-	330w	3.559
	Carolina	7.30	397.6	1.70	1.0	7.5	200	2-9	10	+	350w	4.742
	Carolina	7.30	397.6	1.70	1.0	7.5	400	6-13	09	+	150e	6.450
475	Mean	6.38	217.6	0.56	0.3	6.5	200	3-6	02	-	150e	5.777
	Mean	6.64	264.2	0.50	avg	6.5	200	8-11	09	-	110e	4.114
	Mean	6.91	310.7	0.44	1.0	7.0	400	3-7	04	+	110e	4.996
	Modal	7.29	384.8	0.96	0.3	7.5	400	1-8	08	0	050e	3.083
	Modal	7.29	384.8	0.96	0.3	7.5	400	6-13	10	0	210w	2.809
	Modal	8.00	513.1	0.03	1.0	7.5	400	6-13	08	0	190w	4.903
	Frankel	6.48	213.0	0.49	1.0	6.5	200	1-4	05	+	030e	5.890
	Toro	6.04	143.0	0.50	0.3	6.0	120	9-11	06	-	030e	3.932
	Carolina	7.30	399.8	0.79	avg	7.5	400	400	2-9	+	050e	2.569
	Carolina	7.30	402.7	0.53	1.0	7.5	400	400	2-9	-	250w	3.103
108	Mean	5.99	235.2	-0.02	0.3	6.0	200	9-11	01	0	170e	4.601
	Mean	6.16	264.5	-0.18	avg	6.0	200	2-4	09	-	170e	5.728
	Mean	6.34	293.9	-0.34	1.0	6.5	400	8-11	04	-	070e	4.082
	Modal	5.24	135.2	0.26	0.3	5.8	122	sag			sm09	0.414
	Modal	5.24	135.2	0.26	0.3	5.8	149	sag			sm02	0.521
	Modal	7.29	414.2	-1.07	1.0	7.5	400	6-13	10	+	350w	1.789
	Frankel	5.99	245.5	-0.10	1.0	6.0	200	4-6	04	-	190w	5.212
	Toro	5.80	207.9	0.05	avg	6.0	200	2-4	03	-	170e	5.221
	Toro	5.91	235.6	-0.02	1.0	6.0	200	9-11	10	+	010e	4.972
	Carolina	7.30	407.8	-1.10	1.0	7.5	400	400	1-8	+	010e	2.961

* see explanation of Headings in Table 7

Table 7. Explanation of the Headings of Table 6.

Parameter	Description
RT	Return Time (years)
Deaggregation	The five parameters under this heading relate to the deaggregation of the probabilistic seismic hazard.
Type	Type of deaggregation: mean, mode, fault source, or gridded source (using either the Frankel or Toro et al. ground motion model)
Md	Magnitude from deaggregation
Rd	Distance from deaggregation
Eo	Epsilon – zero from deaggregation
T	Period at which the deaggregation is done (0.3 sec, 1.0 sec, or "avg" – combination of 0.3 and 1.0 second)
Time History	The seven parameters under this heading relate to the time history used to represent the deaggregated seismic hazard. The third through sixth relate to simulated time histories. See Somerville et al. (2001) for more details.
M	Magnitude
R	Distance
Depth	Depth range of fault model, or earthquake name for recorded ground motion.
Slip	Index number of slip model used
Hypo	Location of hypocenter: 0 = fault center, + = between center and north end, – = between center and south end
Az	Azimuth of station with respect to center of north-striking fault, or station name for recorded ground motions
Scale	Scale factor used to match the time history to the probabilistic response spectrum

DISSEMINATION

This report and the CD containing the time histories will be distributed to the three NSF Earthquake Engineering Research Centers, to the Network for Earthquake Engineering Simulation (NEES) Consortium, and other organizations involved in earthquake engineering research and practice in the central and eastern United States.

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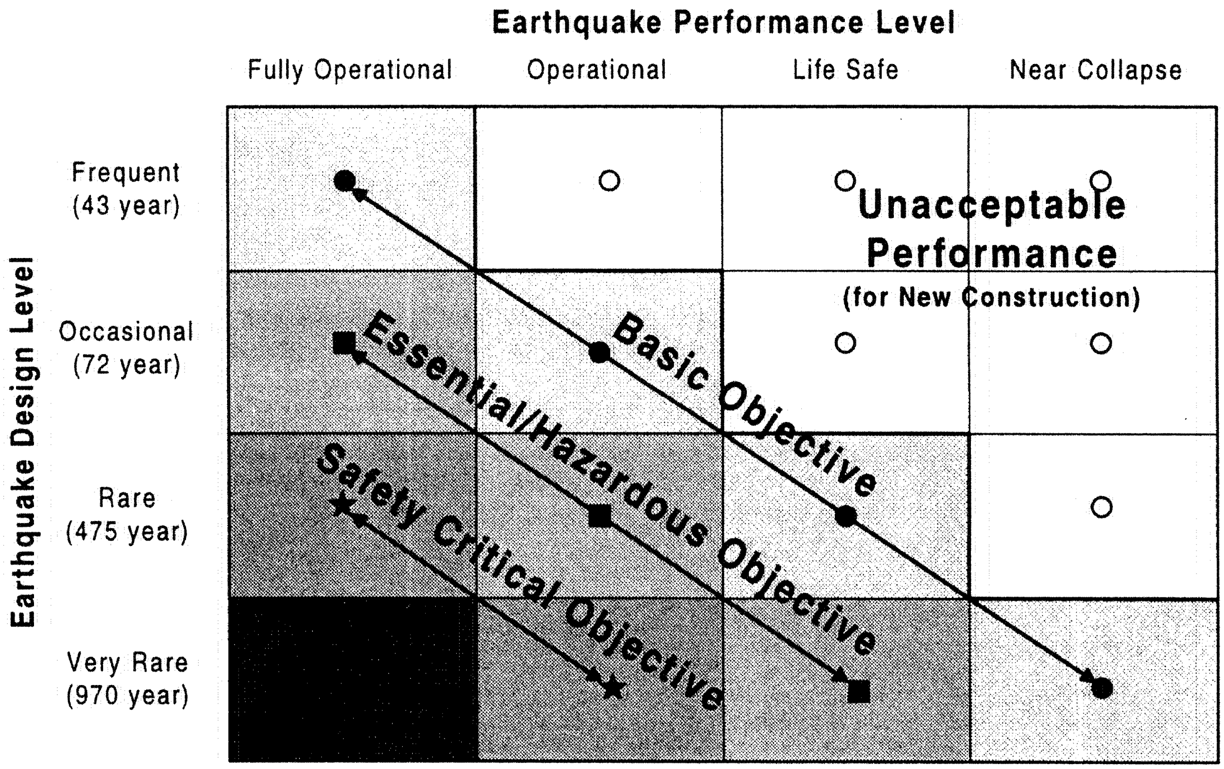

Figure 1. Recommended seismic performance objectives for buildings in SEAOC's Vision 2000 (SEAOC, 1996), showing increasingly undesirable performance characteristics from left to right on the horizontal axis and increasing level of ground motion from top to bottom on the vertical axis. Performance objectives for three categories of structures are shown by the diagonal lines.

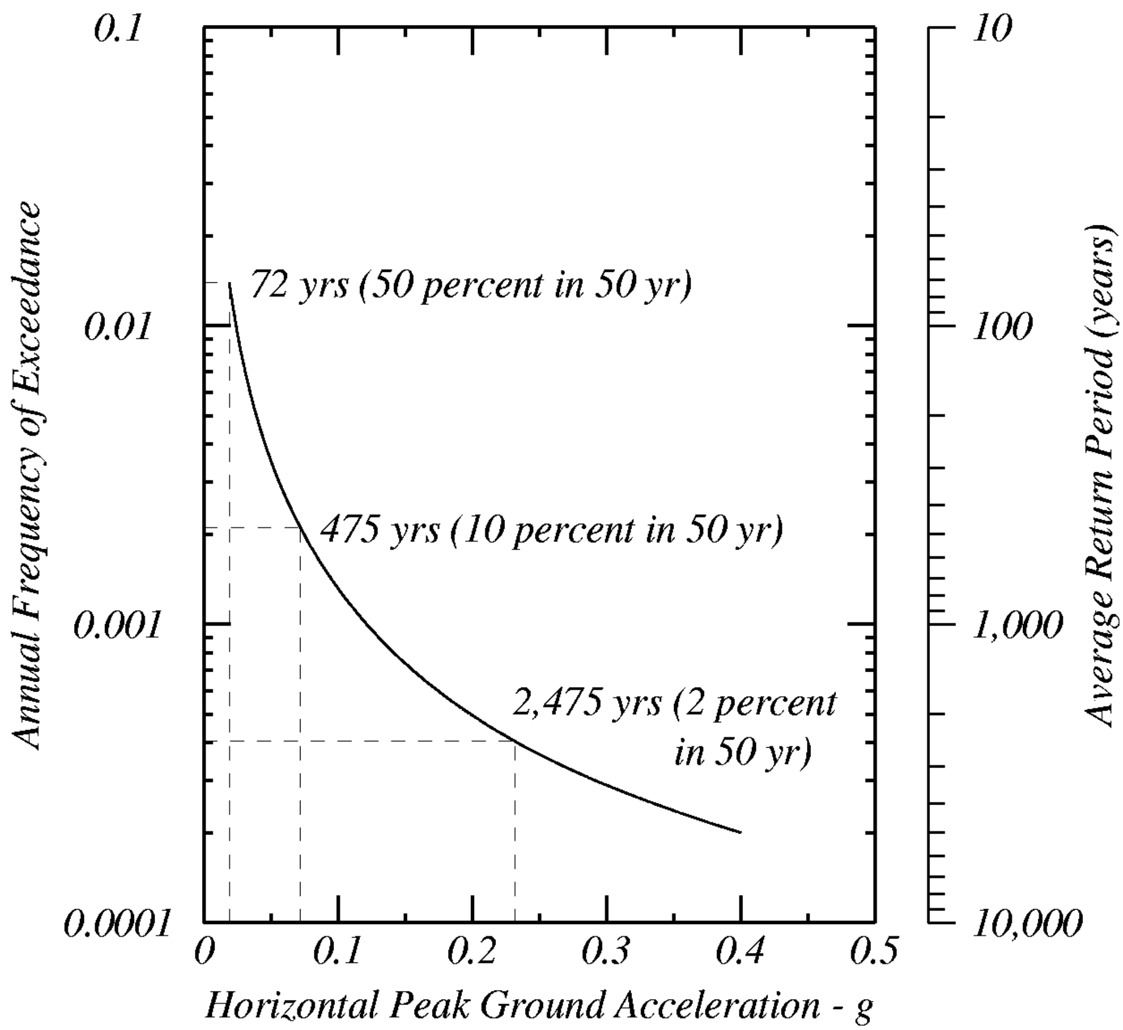

Figure 2. Seismic hazard curve for Boston, showing the decrease in annual frequency of exceedance (or increase in average return period) as the peak acceleration increases. The hazard curve is from the USGS National Seismic Hazard Maps, modified for soil site conditions.

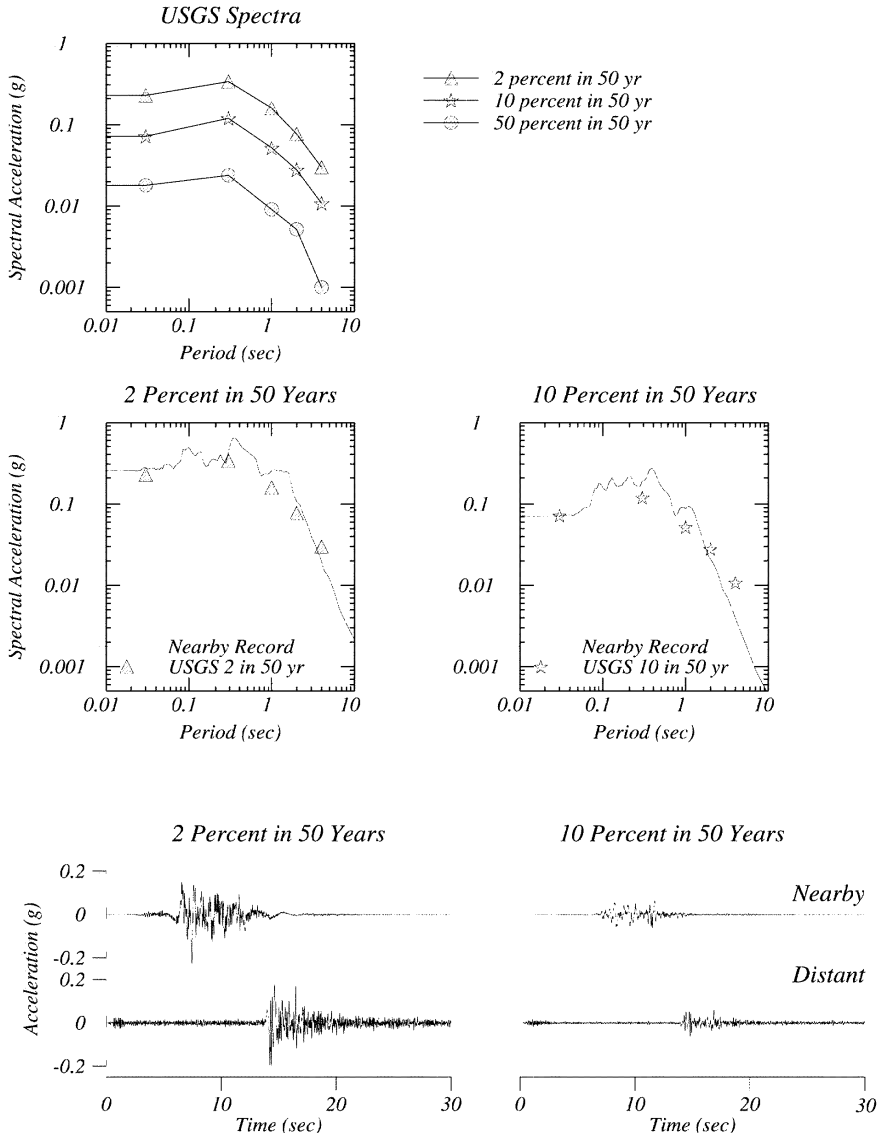

Figure 3. Top: Probabilistic response spectra for three frequencies of exceedance from the USGS National Seismic Hazard Maps, modified for soil site conditions. Middle: Response spectra of scaled simulations of small nearby earthquakes selected to represent the probabilistic spectra for 2% in 50 years and 10% in 50 years. Bottom: Scaled simulations of small nearby earthquakes and larger more distant earthquakes used to represent the probabilistic spectra for 2% in 50 years and 10% in 50 years. Source: Somerville *et al*., 1998.

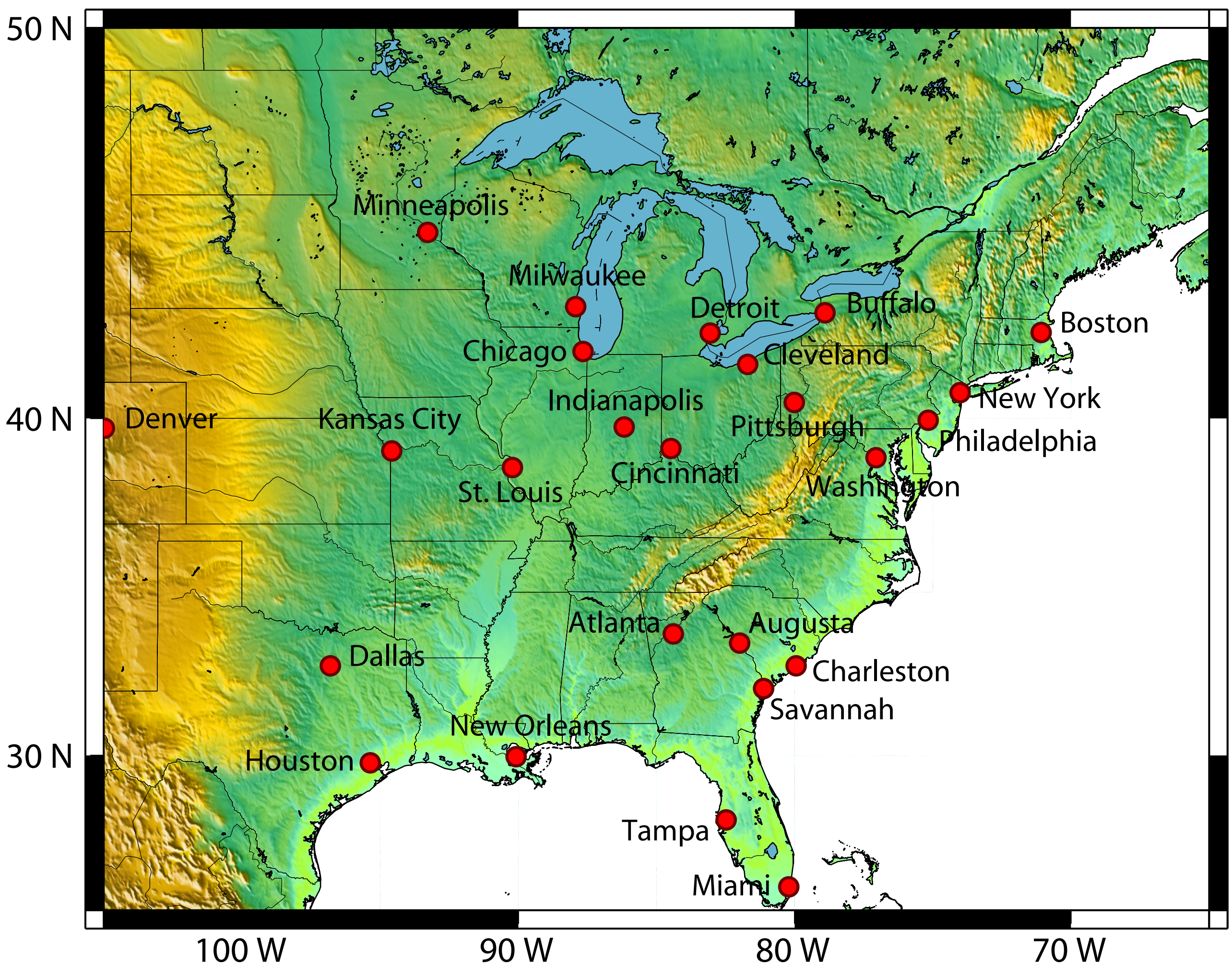

Figure 4. Locations for which time histories were generated.

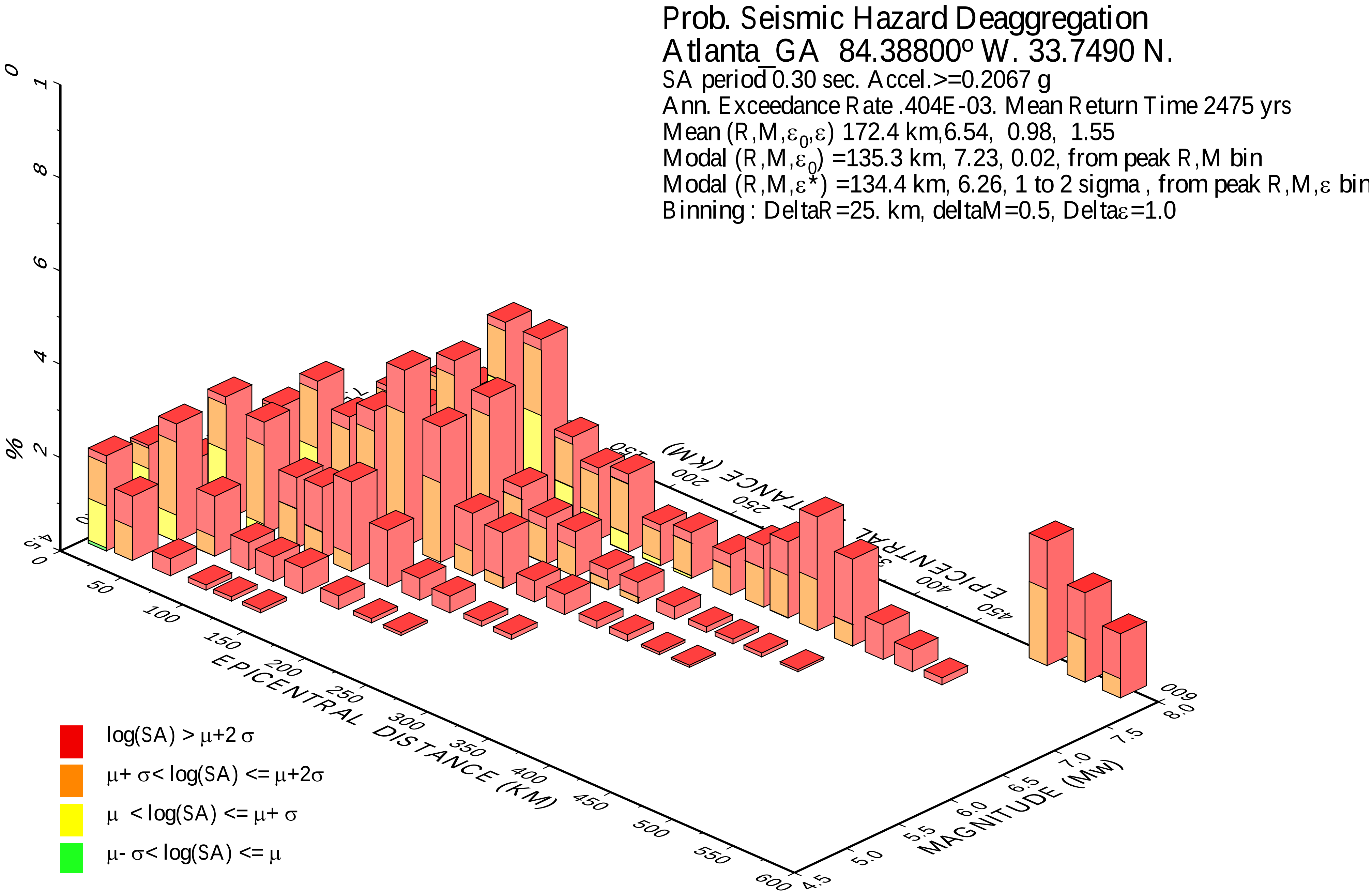

Figure 5. Magnitude - distance - epsilon deaggregation of hazard in Atlanta for a return time of 2475 years and a period of 0.3 seconds. Source: USGS

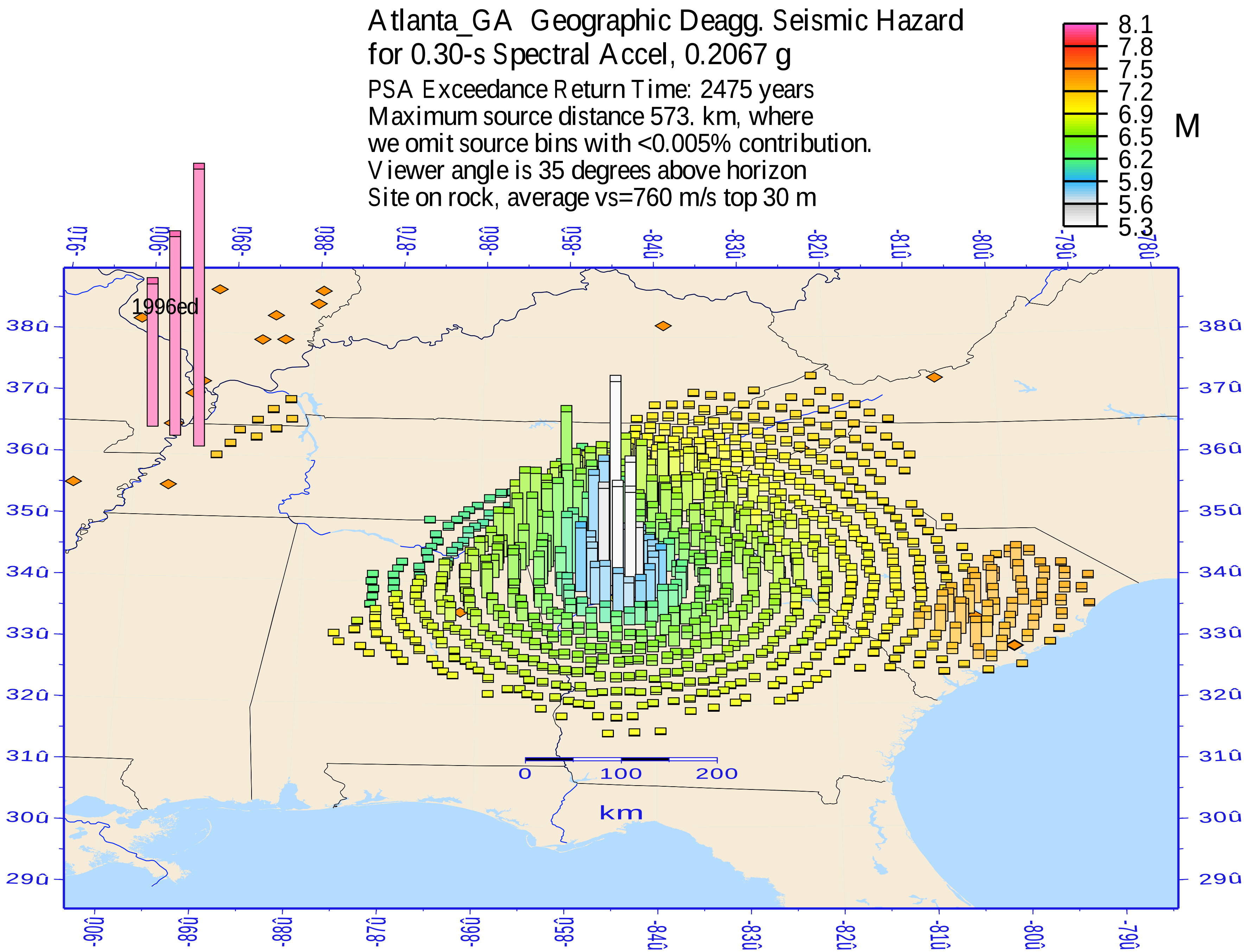

Figure 6. Geographic deaggregation of hazard in Atlanta for a return time of 2475 years and a period of 0.3 seconds. Source: USGS

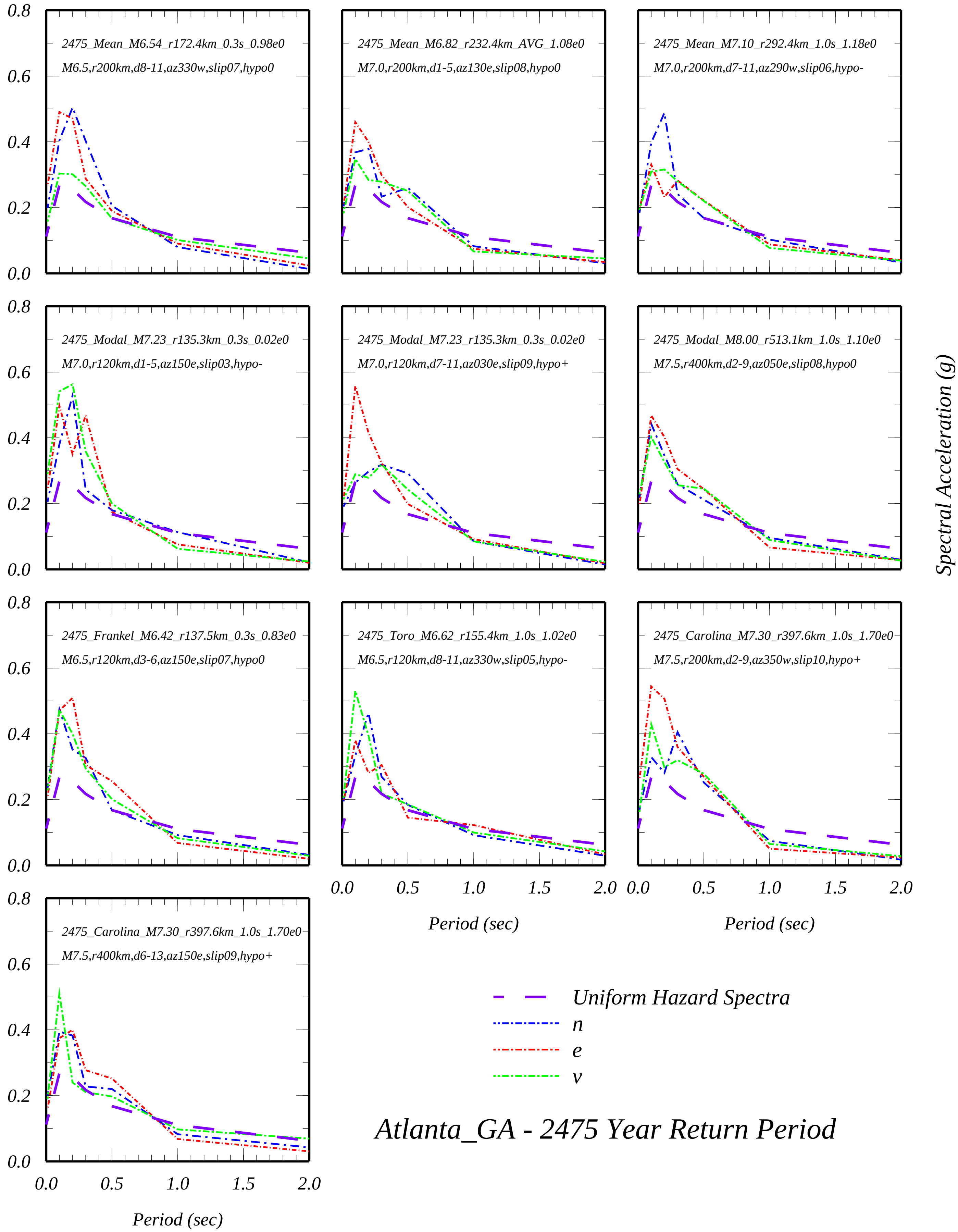

Figure 7. Comparison of USGS probabilistic response spectrum for 2475 year return period at Atlanta GA with response spectra of ten selected time histories, after scaling. Labels are explained in Tables 6 and 7.

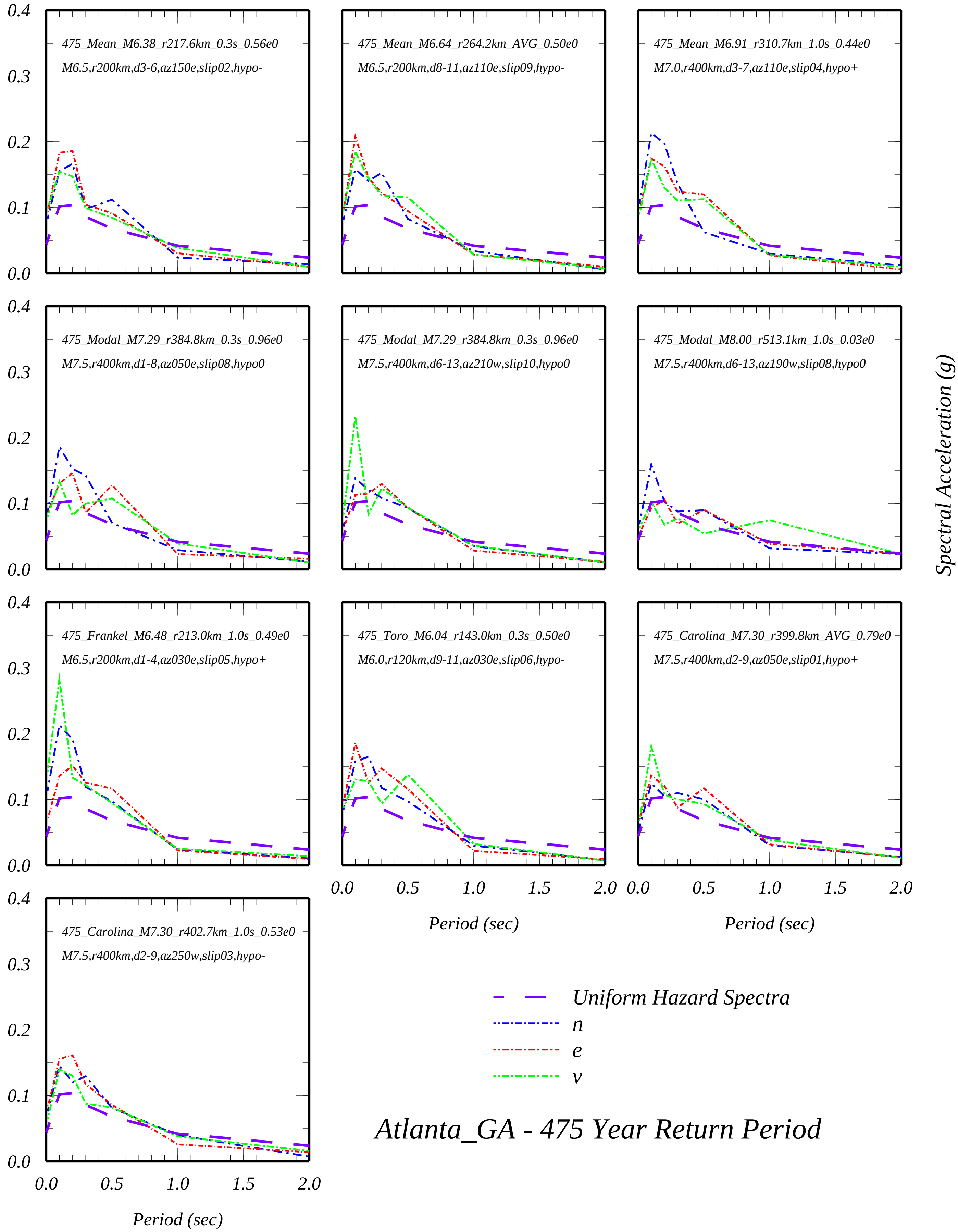

Figure 8. Comparison of USGS probabilistic response spectrum for 475 year return period at Atlanta GA with response spectra of ten selected time histories, after scaling. Labels are explained in Tables 6 and 7.

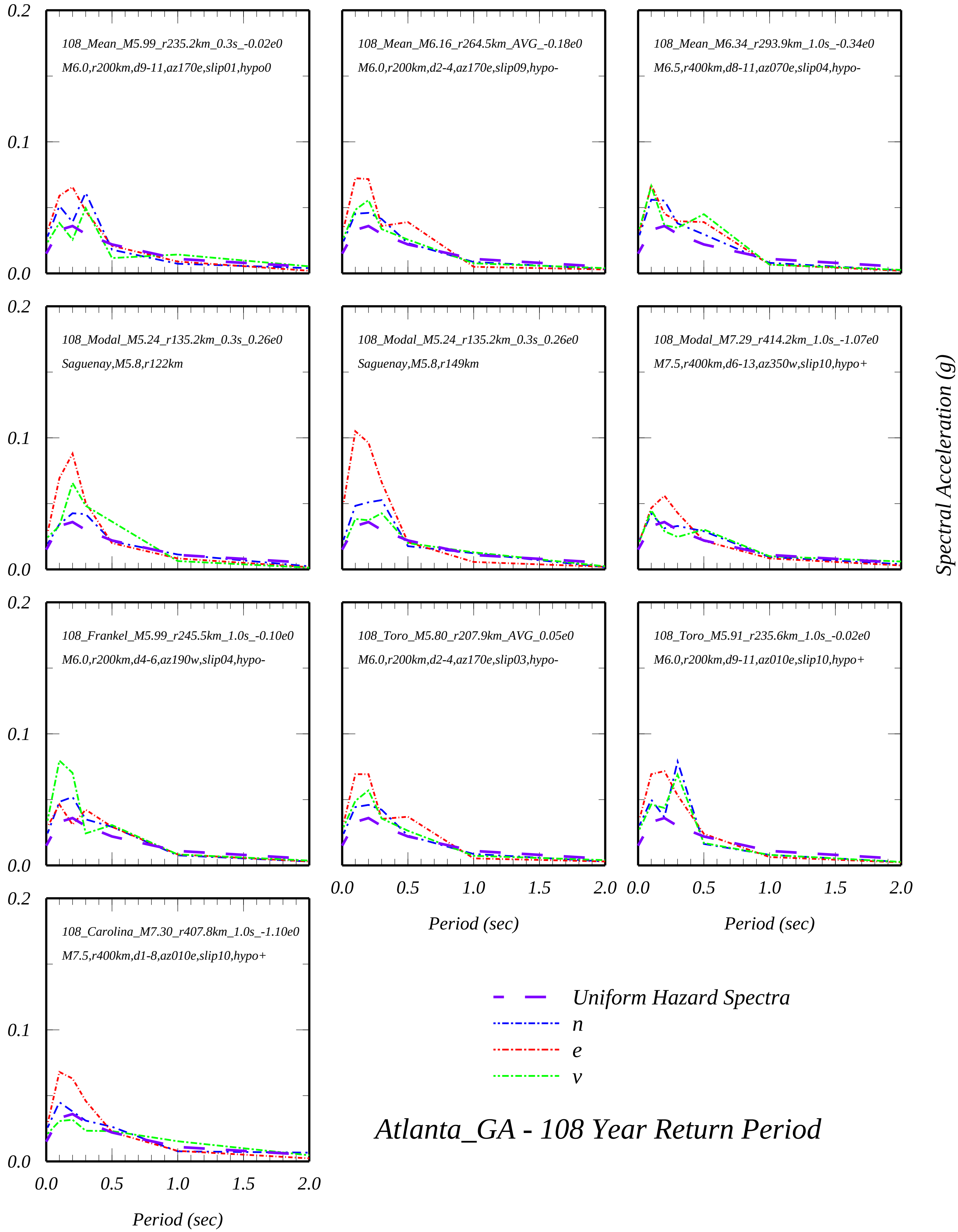

Figure 9. Comparison of USGS probabilistic response spectrum for 108 year return period at Atlanta GA with response spectra of ten selected time histories, after scaling. Labels are explained in Tables 6 and 7.

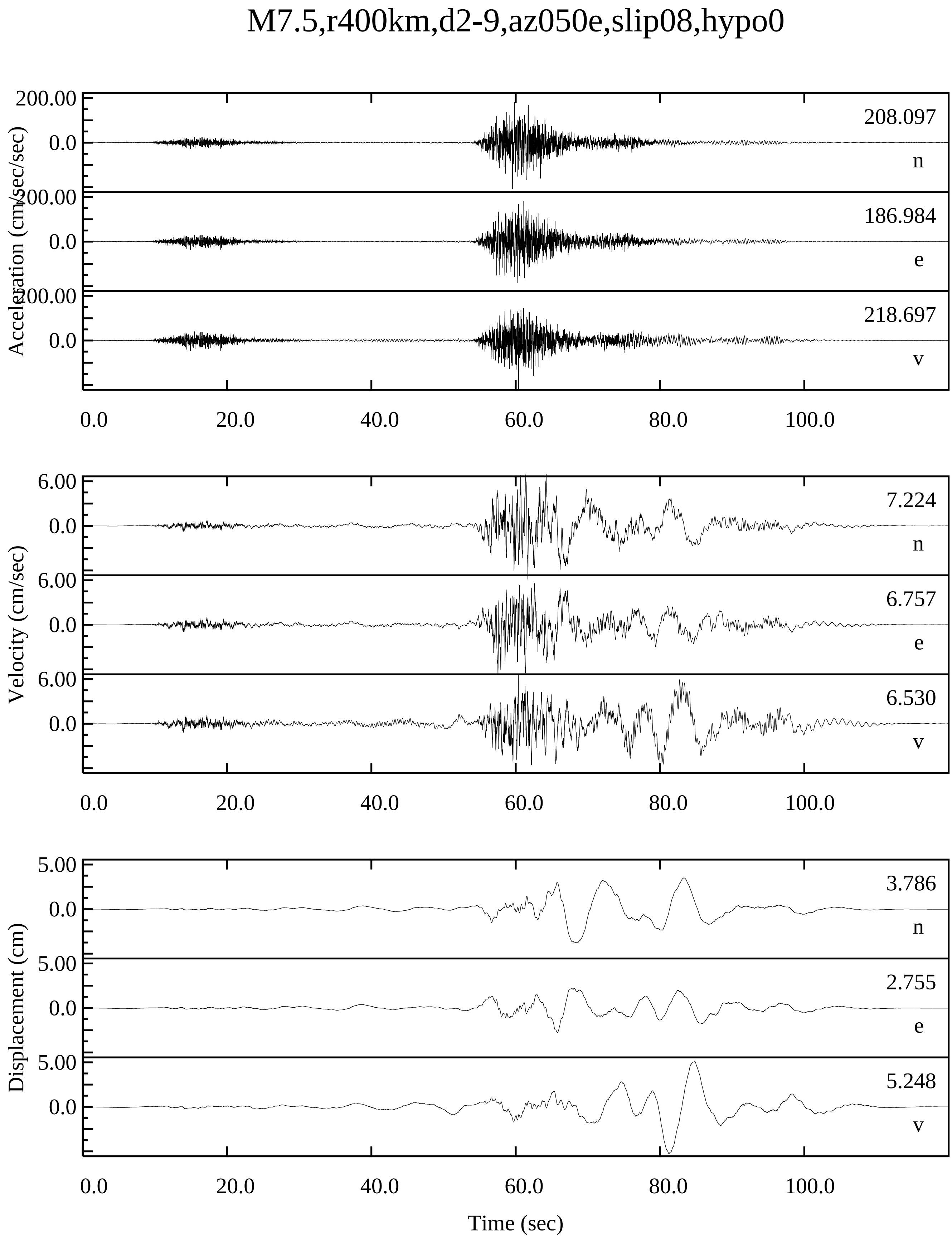

Figure 10. Sample time history selected and scaled to represent the USGS probabilistic response spectrum for 2475 year return period at Atlanta GA. Labels are explained in Table 7.

M6.5,r200km,d8-11,az110e,slip09,hypo-

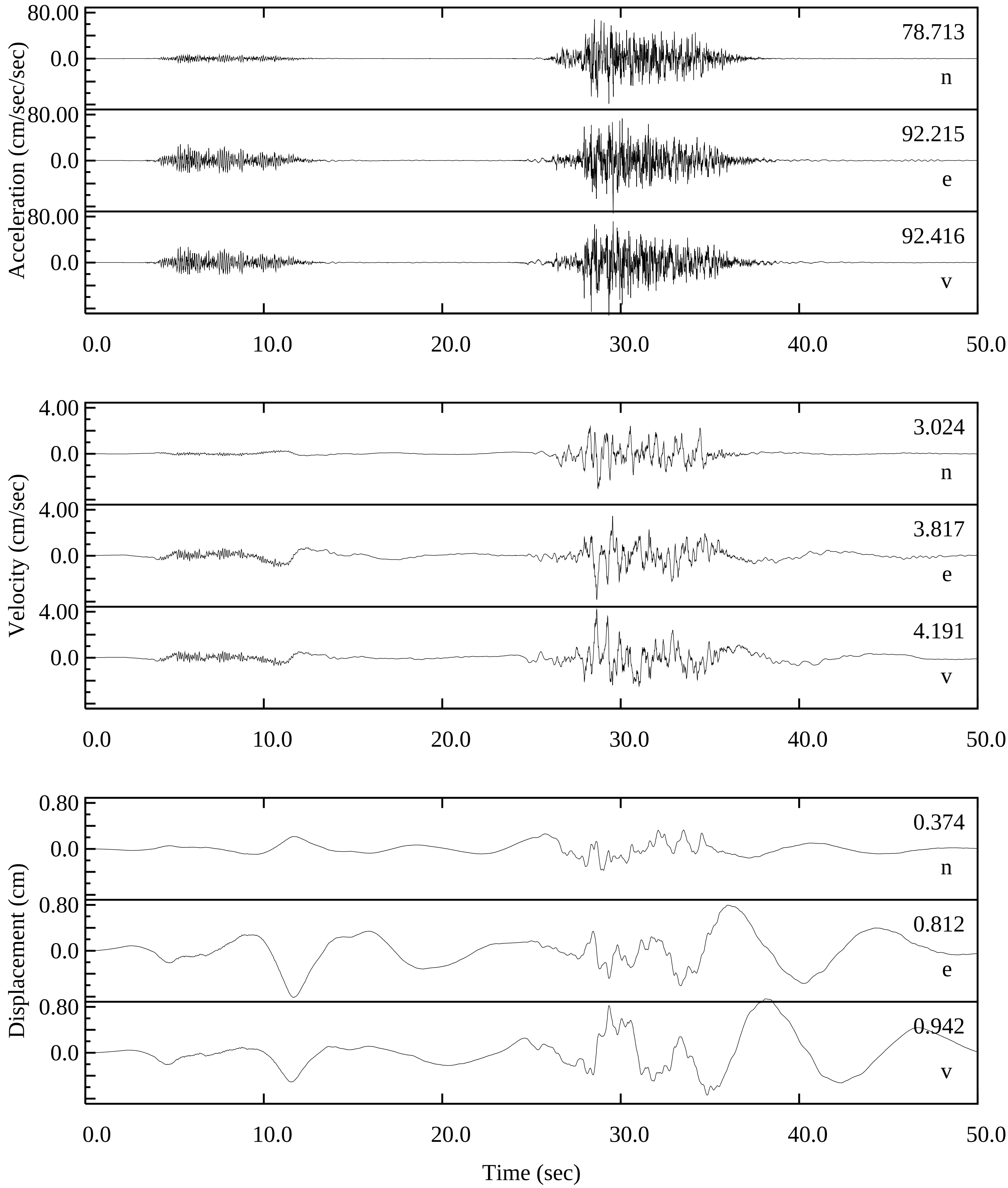

Figure 11. Sample time history selected and scaled to represent the USGS probabilistic response spectrum for 475 year return period at Atlanta GA. Labels are explained in Table 7.

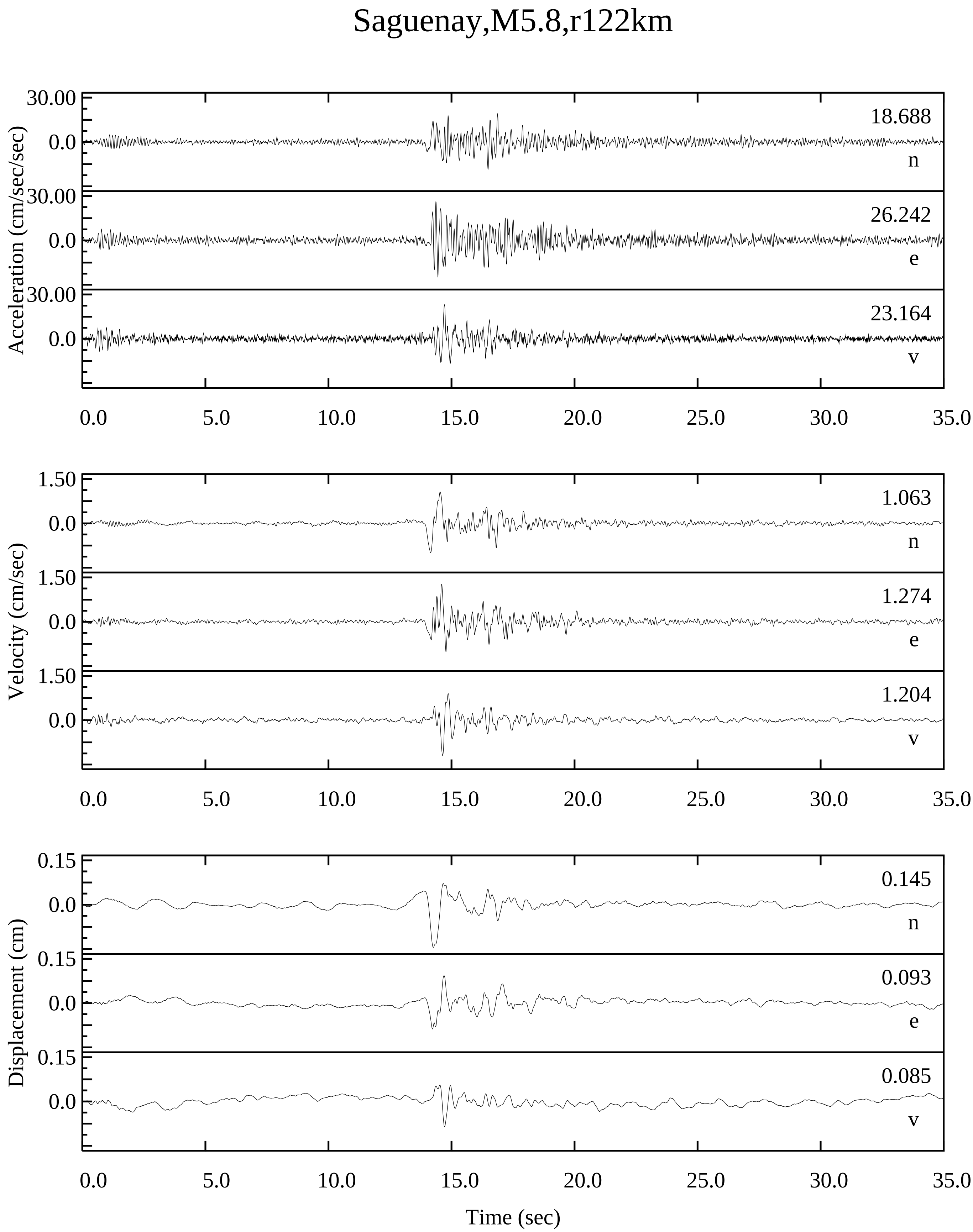

Figure 12. Sample time history selected and scaled to represent the USGS probabilistic response spectrum for 108 year return period at Atlanta GA. Labels are explained in Table 7.